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River flow prediction through rainfall–runoff modelling with a probability-distributed model (PDM) in Flanders, Belgium

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ABSTRACT

The hydrological probability-distributed model (PDM) is widely used all over the world and its applicability has also been investigated in Flanders, Belgium. Rainfall–discharge relations for all gauging stations installed on non-navigable watercourses were modelled over a long succession of monitoring years. In all, 1456 years were modelled. Typical characteristics (peak flow, volumes) of modelled series are compared with observations. Based on the relatively long time series, reliable discharge values can be generated with the PDM. Water volumes and peak characteristics are very close to the observed values. The set of 98 PDMs was analysed and clustered. Three cluster approaches were considered: a single-parameter approach, a parameter set approach and an approach with known cluster zones, delineated on hydrological flow characteristics. The single-parameter approach, the parameter set approach and the combination of both gave less detailed regional information than the clustering on hydrological characteristics.

1. Introduction

Predicting the runoff from a specific catchment has been the subject of numerous studies for many years. The need for such predictions remains great, especially in densely populated and flood-sensitive areas like Flanders in Belgium. In general, a good conceptual model takes into account the physical description of the runoff phenomena, with parameters reflecting the characteristics of the catchment area that play a role in these phenomena.

The hydrological probability-distributed model (PDM) has applications worldwide (Young and Reynard, 2004; Blyth and Bell, 2004; Moore, 2007). In Flanders too, the PDM is used. Willems et al. (2001) postulated that the PDM model is well structured compared with other model concepts.

In an intensive modelling campaign, 98 monitored catchment areas in Flanders were modelled with the PDM (1456 recording years). The statistical characteristics (peak flow rates, discharge volumes) of the modelled series were compared with the observed values. The potential of the PDM concept for modelling the whole of Flanders was investigated.

This paper illustrates the modelling behaviour of the PDM for one of these 98 catchments. The modelling strategy and model results are shown.

A collection of 98 parameter sets from one single modelling campaign has great potential for regionalisation purposes. Both a single-parameter approach and a parameter set approach were applied. The parameters were screened and clustered. This clustering was compared with the hydrological regions in Flanders.

2. Methods

2.1. PDM description

The PDM (Moore, 2007) is a conceptual hydrological model. The PDM concepts are explained briefly. For a detailed

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description of the PDM and all model parameters, the reader is referred to Moore (2007). The conceptual structure of the model is shown in Fig. 1.

The PDM describes the catchment area as a collection of reservoirs, each with a different content. This collection of soil moisture reservoirs (from shallow to very deep) is mathematically described by a probability distribution. In most cases, a Pareto distribution is supposed, which is described by three parameters (c_{max}, c_{min}, b):

$$F(c) = 1 - \left(\frac{c_{max} - c}{c_{max} - c_{min}}\right)^b, \quad c_{min} \le c \le c_{max}.$$

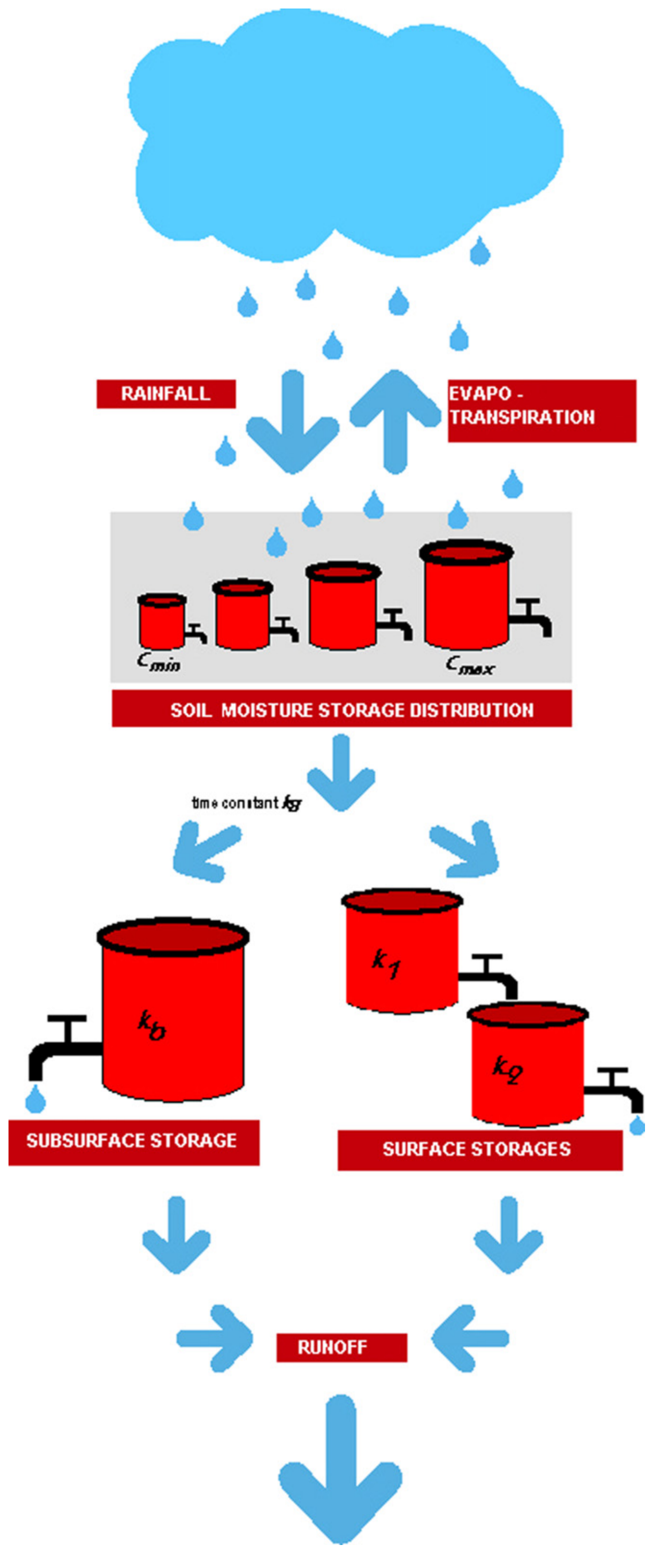

Fig. 1 – The PDM model structure.

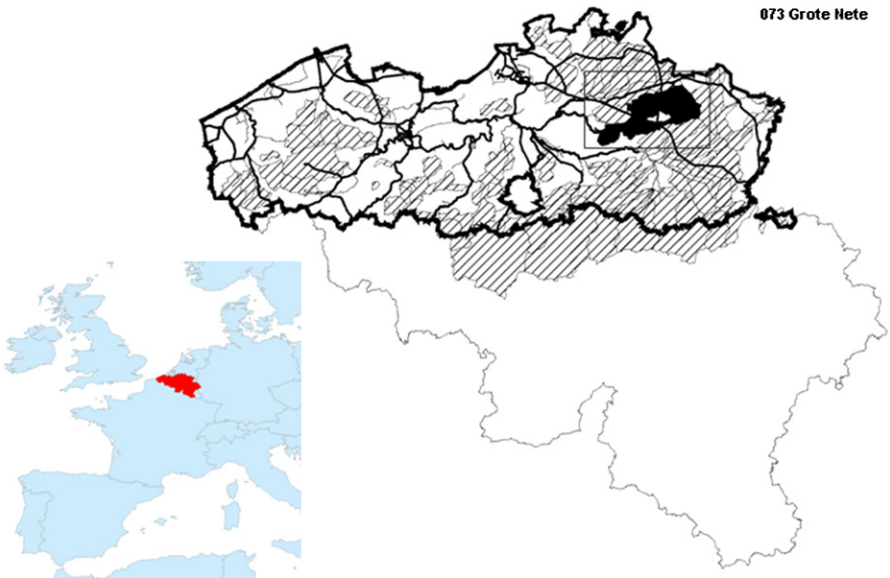

Fig. 2 – Location map of the study area (Flanders, Belgium). The hatched catchments were all modelled with PDM. The black catchment (Grote Nete, Hulshout) is discussed as example.

where c is the moisture content, c_{min} and c_{max} are parameters defining the minimum and maximum soil moisture storage capacity, and exponent b is a further parameter. To obtain a picture of the average content of the reservoirs (average soil moisture content in the catchment area), S_{max} (mm) is used:

$$S_{max} = \frac{c_{max} + bc_{min}}{(b+1)}.$$

The soil moisture reservoirs are filled with rainfall. Water evaporates from the filled reservoirs, and a certain volume drains as recharge to groundwater. This recharge is controlled by the groundwater drainage time constant k_g (h). Recharge is limited by S_t, the threshold below which water is being held under soil tension. Full reservoirs overflow when there is too much rainfall. The overflow water is conceptually modelled as the runoff or fast discharge. This simple storage concept and the probability distribution of these storages inside the catchment form the base of the PDM. The processes in the model are strongly related to the physically observed processes of recharge to groundwater, evapotranspiration and runoff production.

The resultants of the water balance "rainfall − evapotranspiration − soil storage change = runoff + recharge" gives, via a mathematical description, a modelled runoff in the watercourse. Groundwater discharge is, by nature, a slow discharge component and is simulated with one additional reservoir (cubic storage), with a large storage time constant k_b. Runoff is modelled as a succession of two linear reservoirs (with relatively small storage time constants k_1 and k_2). The combination of those reservoirs makes it possible to approximate the shape of the hydrograph.

Additional in- or outflow from or to the catchment is modelled by one parameter q_{const}.

The PDM used here is that provided in the Infoworks© modelling software (Wallingford Software, 2000) that supports part of the PDM model code developed at the Centre for Ecology and Hydrology (CEH Wallingford, 2005). This model has 12–14 parameters (depending on distribution and reservoir concept), which can each be adjusted in a calibration procedure and validated for future events. Identification of the most sensitive parameters by preliminary model runs reduced the number of parameters in the calibration to 9. Only the most sensitive parameters were adjusted and explained above.

A PDM was set up for each of the 98 gauging stations on the non-navigable watercourses in Flanders, Belgium (Fig. 2). Five representative storms were selected to calibrate the model (periods with summer storms if no vegetation growth occurs in the watercourse, periods with winter storms, as well as periods with relatively low flows). The model was calibrated on the basis of the hourly flow values of these periods and complete year-to-year monitoring series of daily flow values.

Catchment area rainfall was manually calculated on the basis of daily sums from 200 storage raingauges and hourly values from 25 recording raingauges. The daily rainfall amounts for the catchments were obtained via Thiessen polygons. The distribution in time of the nearest recording raingauge was used to spread the Thiessen sum over the day. This method was found to be the most consistent in handling all available rainfall series over their lifetime, and in reducing errors in concentration time by using one recording raingauge and not an interpolation on an hourly basis.

It is known that a random parameterisation hardly results in a single-optimum distribution. Model parameters cannot be treated as independent individual parameter values but instead as complementary parameter vectors (Bárdossy, 2007). Moreover, Heuvelmans et al. (2004) pose that knowledge on the spatial variation in parameter optima can improve the performance of a model. Therefore the modelling work was done by one single person, during one long modelling campaign, introducing a subjective but coherent view on

parameter optimisation. The calibration procedure specifically made sure that estimates of storage time constants were relevant and coherent, the separation of drainage and fast runoff was optimal and the correspondence between total simulated and observed discharge resulted in both small relative root mean squared errors (RRMSE) and large Nash–Sutcliffe efficiency (NSE) coefficients. The RRMSE is calculated as the ratio of the RMSE to the mean observed flow $\bar{Q}$. The Nash–Sutcliffe efficiency coefficient is used to assess the predictive power of hydrological models (Nash and Sutcliffe, 1970) and is defined as

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{T}(Q_t - q_t)^2}{\sum_{t=1}^{T}(Q_t - \bar{Q})^2}$$

with Q_t the observed flow at time t, q_t is the modelled flow at time t and $\bar{Q}$ is the mean of the observed flows over the T values of the summation (the total time steps in the monitoring period).

The model was validated by simulating the total monitoring period. Monitoring periods varied from 5 to 45 years, with an average of about 15 years per gauging station. Many studies compare only a few storms. However, this study uses a more severe test, validating the model over the total monitoring period, rather than over a few storm periods. First, the total volumes of river flows are compared over the complete monitoring period. Then, the whole series are analysed on extreme events. Both the annual maximum peak flows and the annual maximum storage volumes were distilled out of the observed and modelled series and were processed per water year (October–September). The storage volume of a flood hydrograph above certain flow rates is represented as B_{03}, B_{08}, whereby indices 03 and 08 are the thresholds (30% and 80% of the average annual high-water maximum) above which the storages are calculated. The storages are expressed in mm (1 mm = 10 m^3 per ha). Storages can cover several floods. A new storage only starts when a previous one has run empty completely.

For the analysis of the model results, the thresholds B_{03} and B_{08} were mainly taken into consideration. They were found to be representative for the most extreme events (B_{08}) and common flood volumes after moderate rainfall (B_{03}). Preliminary examinations indicated that conclusions about model behaviour based on other thresholds (B_{01}, B_{02}, B_{04}, ...) are similar to or less clear than the conclusions based on B_{03} and B_{08}.

For extreme value analysis, the Gumbel distribution was used. Here, the Gumbel reduced variable G_{ij} is calculated as

$$G_{ij} = e^{-e^{-y}}$$

where $y = (x_i - u)/a$ represents the reduced variable, x_i is an individual peak flow rate, and u and a are two parameters of the Gumbel distribution (average and spread).

The parameters of the Gumbel distribution were calculated by using probability-weighted moments.

A calibration-validation loop was carried out. Models with satisfactory validation results (on flow volume, maximum peak flows and maximum storages) are withheld, others were recalibrated, incorporating effects on volume, peak flows and flow storages.

2.2. *The study area*

The study region consists of the Northern part of Belgium (Flanders) wherein the smaller, non-navigable watercourses were modelled. Flanders covers an area of approximately 20,000 km^2. The 98 modelled catchments (some of them nested) cover a total area of 7500 km^2, and the individual catchment areas range from 200 ha to 800 km^2. As the study area is relatively small, climatic conditions are more or less uniform regarding the time-scale (an average of almost 15 years per model). Summer storms are more intense and shorter, while in winter less intensive but more frequent storms occur. Some stations suffer from plant growth in the watercourse, so flow values cannot be deduced from level gauging. Periods with plant growth were excluded from the analysis.

Flemish catchments are characterised by a relatively wide spread in flow characteristics. Voet (2000) worked on the estimation of runoff peaks through catchment characteristics. He found three homogenous regions where flood peak changes by return period obey the same law. This research was based on the *R*-test for homogeneous regions of Wiltshire (1986). Geographical proximity as well as similar catchment and flow characteristics was incorporated in this research, the latter appearing to be the most discriminating factor. Voet (2000) found that the Flemish catchments can be clustered in at least three hydrological regions. The catchments in the first region are characterized by relatively low-flood peaks (low Qpeak, LQ) and rather limited variation in peak flows (low coefficient of variation, LCV). This region was named LQLCV and is characterised by sandy soils in a relatively flat area (Campine). Catchment areas of the dry loamy area (LQ high coefficient of variation, LQHCV) can be grouped on the basis of their relatively small flood peaks (low Qpeak) with relatively high variation (HCV). They are characterized by moderate slopes, a loamy soil and a deep permeable quaternary layer. This LQHCV-group is less uniform in catchment characteristics than others. A third group consists of the hilly catchment areas (hilly loam) where the peak flow is characterized by relatively high-flow rates with high variation (high Qpeak HCV, HQHCV). This region has moderate slopes, loamy to sandy loam soils and a relatively thin quaternary layer. There is also a fourth region, the typical polder region (no slope, clay soil), for which insufficient time series are available at present. Three stations differ significantly from all others. They flow in a cretaceous formation at the edge of Flanders, and are characterised by deep soils, with high-infiltration capacities. To reduce cluster numbers, one has chosen to incorporate these stations in the nearest LQHCV region.

3. Results

3.1. *Model example*

One of the 98 models is discussed below by way of example. A similar analysis of the other 97 models was carried out.

The river-gauging station 073 on the Grote Nete in Hulshout (Fig. 2) has been operational since 1976. In summer months, vegetation growth can appear at this station. For model

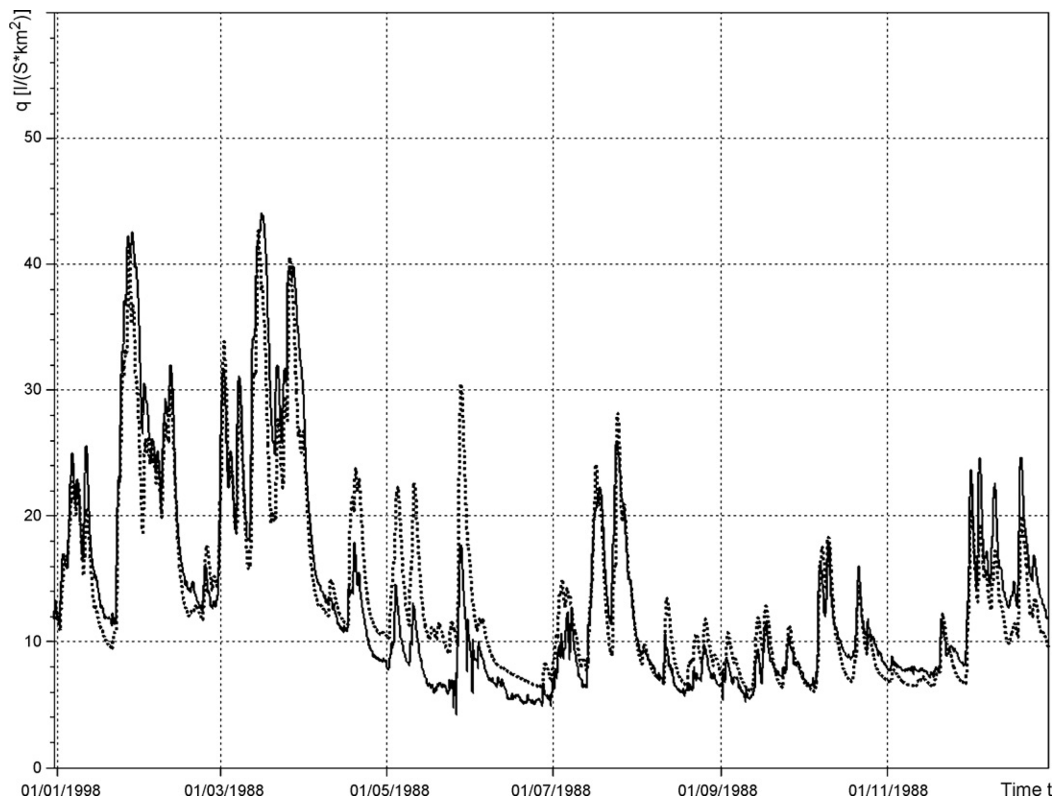

Fig. 3 – One year (1988) of specific discharge [l/(s km^2)] through the Grote Nete at Hulshout. Observed flow: solid line; simulated flow: dashed line.

calibration, summer storms were therefore not taken into account. The station monitors a (relatively large) catchment area of 44,000 ha, entirely located in a sandy area. Table 1 shows the PDM parameters obtained.

Fig. 3 shows one year out of the 25 simulated years. The NSE coefficient for the complete monitoring series is 0.8, which is very large for a 25-year simulation. The RRMSE indicates the average error being 28% of the average observed (low) flow. The results show that both peaks and volumes are estimated accurately. Fig. 4 shows the cumulative volume over the whole monitoring period. The maximum deviation over a 25-year period is only a few percent of the total volume.

Fig. 5 shows the results of the frequency analysis for annual high-water maxima (Fig. 5(a)) and annual storage maxima (Fig. 5(b) and (c)). The correlation between observed and simulated peak flows is 0.94 and the correlation for the storages above both thresholds (B_{03} and B_{08}) is 0.99. The results for both volumes and peak flows match very closely.

Only the highest observed peak flows are modelled quite higher. This can be explained by the hydraulic effect of flooding. When larger volumes flood, the shape of the hydrograph is deformed in a way that cannot be modelled by the simple two-storage approach. This deformation is not taken into account by the model. As a result, the model overestimates the peak flow. The corresponding storage (volume), however, is estimated accurately.

The results of the Grote Nete model are typical for the PDM results in the Flemish catchment areas. The statistical analysis shows that the PDM can produce reliable peak flow and storage volume values for high-return periods. Modelling results of the PDM can be used for design purposes. The accuracy on individual flood peaks may be improved through a better input of rainfall and evapotranspiration depths, their timing against river flows and by more accurate measurements at the river-gauging stations.

Table 1 – PDM parameter values for the Grote Nete at Hulshout

Area (km^2)	443.5
c_{max} (mm)	1000
c_{min} (mm)	70
b	0.75
k_1 (h)	40
k_2 (h)	14
k_b (h/mm^2)	0.01
k_g (h)	8800
S_t (mm)	0
q_{const} (m^3/s)	0

3.2. *Overall model results and regionalisation*

In all, 1456 years were modelled in this way, with an average NSE coefficient of 0.58. Parameter sets were withdrawn when less than 35% of the variation was modelled (NSE coefficients range from 0.4 to 0.85). For 10 catchments, no satisfactory parameter set was found. All of them could be explained as a result of poorly defined rating curves. Table 2 illustrates the

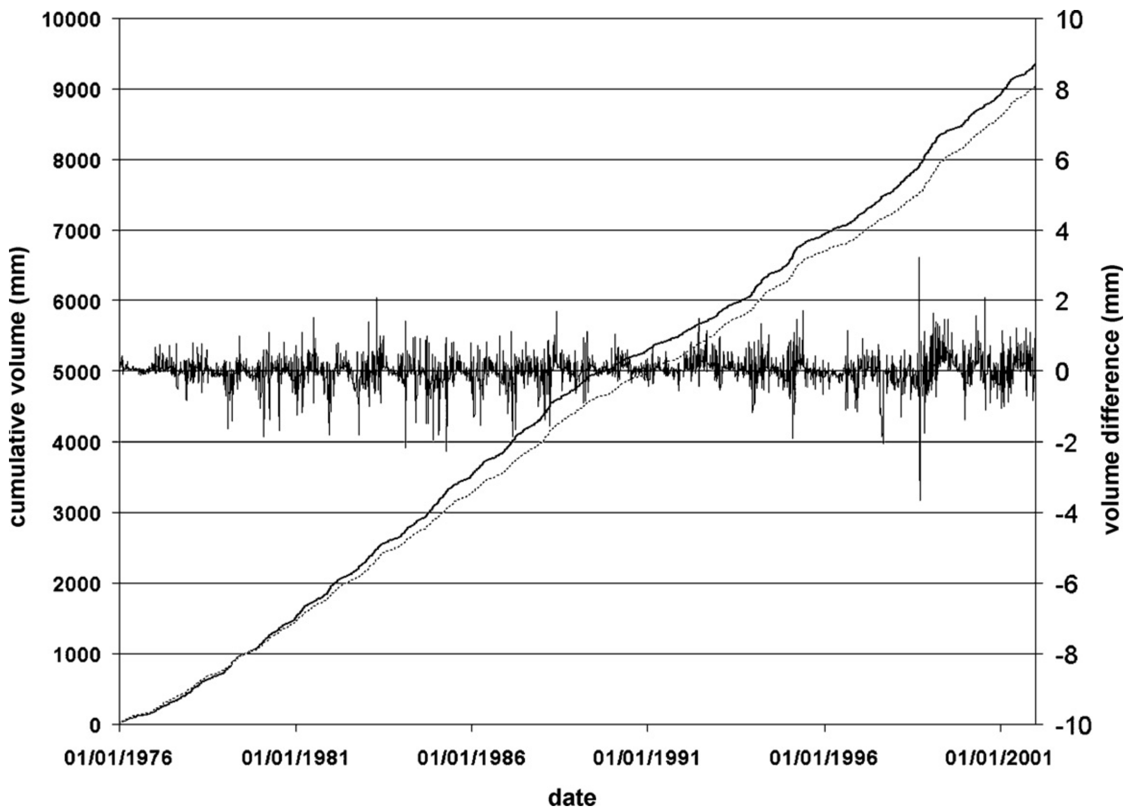

Fig. 4 – Accumulated volume and volume differences between observed flow (bold line) and simulated flow (dashed line) through the Grote Nete at Hulshout, for 25 years. Differences are expressed in mm and calculated as "simulated minus observed".

PDM parameter ranges for the 88 catchments. This large collection of parameter sets is well suited for regional research. It is clearly apparent that Flanders cannot be treated as one homogeneous region.

The transfer of model parameters from one catchment to another has been the subject of recent research (Young and Reynard, 2004; Parajka et al., 2005; Bárdossy, 2007). The spatial variability of model parameters can be looked at in several ways. Heuvelmans et al. (2004) propose a combination of two approaches. In a single-parameter approach the parameters are considered one by one, ignoring the relations between them. The parameter set approach examines the parameter set as a whole, thereby incorporating the entire hydrological process. Heuvelmans et al. (2004) suggest applying both techniques independently and interpreting them in combination. This should lead to a physical, understandable and effective parameter regionalisation.

Table 2 – Parameter ranges in Flanders

	Minimum	Mean	Maximum
c_{max} (mm)	160	944.6	5000
c_{min} (mm)	0	59.8	300
b	0.1	0.51	2
k_1 (h)	0.9	14.7	40
k_2 (h)	0.1	4.2	15
k_b (h/mm^2)	0	175.5	5000
k_g (h)	700	10,265	25,000
S_t (mm)	0	25.3	150
q_{const} (m^3/s)	−4.08	−0.13	0.03

Spatial variation of parameter values should reflect hydrological characteristics of the measured series. Voet (2000) delineated hydrological regions by using flow characteristics and catchment properties. Regression analysis showed a significant correlation between flow characteristics and catchment properties within three regions. One can assume an analogue relation between catchment characteristics and PDM parameter values.

An additional analysis of parameter sets within known hydrological clusters can most likely explain even more parameter variation.

For this regional analysis we have chosen four parameters, which are conceptually related to the soil characteristics of the catchment: c_{max}, c_{min}, b, k_g.

3.3. *Single-parameter approach*

Fig. 6(a)–(d) show the zones that were delineated for all four parameters. Parameters were log-transformed to reduce errors due to non-normality. For all parameters two groups can be observed ($p \leq 0.01$, Kruskall–Wallis H-criterion). A third group consists of the three stations in the Cretaceous region. In the single-parameter approach, this group is not shown.

The parameters k_g (groundwater recharge time constant) and c_{max} (deepest soil moisture reservoir) show a significant geographical component in Flanders. The c_{max}-parameter

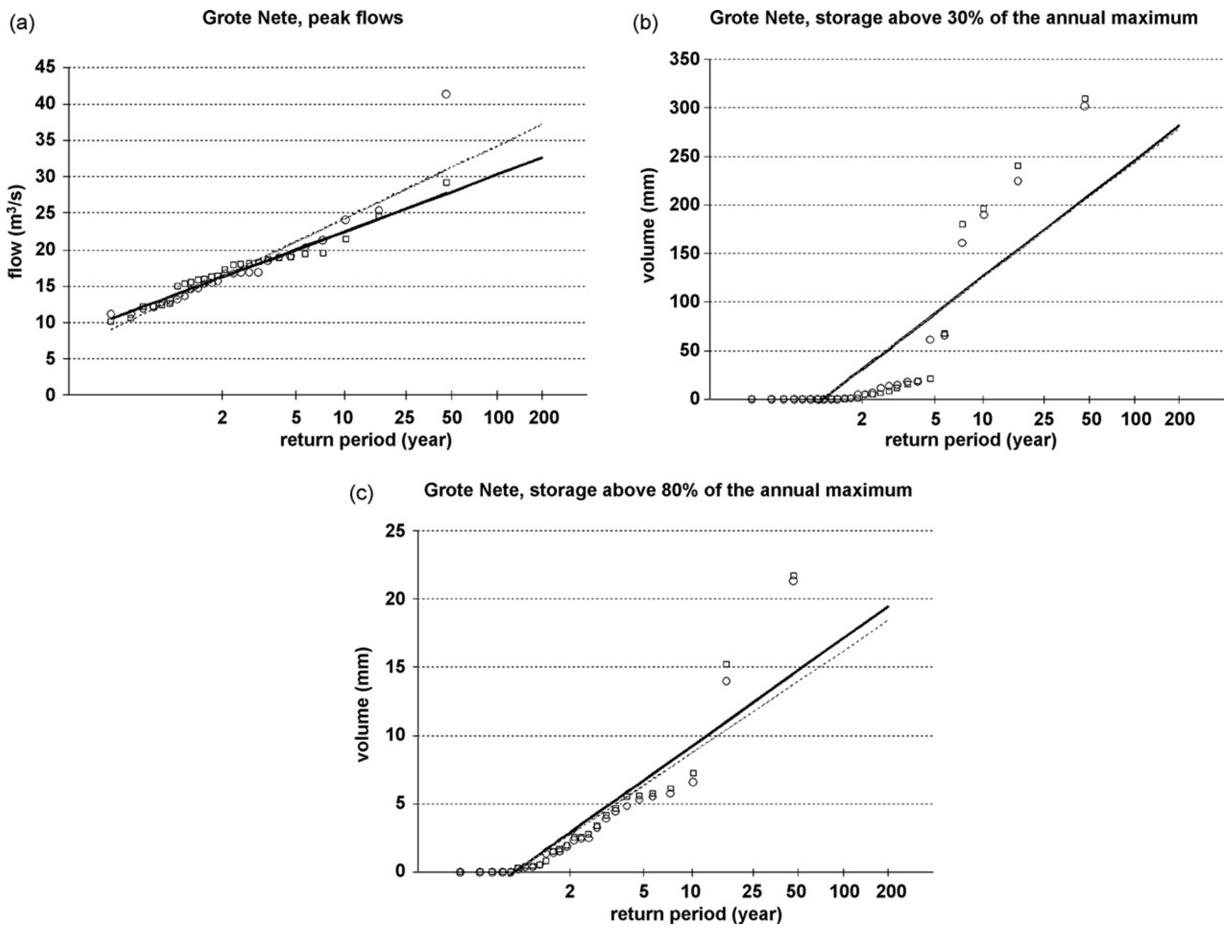

Fig. 5 – Extreme value analysis of peak flows (a) and volumes (B_{03}: b; B_{08}: c): comparison of observed (solid line, rectangle) and simulated (dashed line, circle) values. The highest peak caused flooding, which explains the difference between simulated and observed flow. Volumes for this peak match.

shows an east–west gradient with high values in the eastern part of Flanders and low values in the west. A north-south gradient can be found for the k_g-values, with high values in the southern part and smaller values in the north. One can imagine a combination of both distributions being the reflection of the three hydrological regions in Flanders.

The geographical clustering for values of the parameters b and c_{min} is less clear. It can be assumed that catchment characteristics without well defined geographical allocation (land use for example) dominate these parameters and prevent the geographical clustering.

3.4. *Parameter set approach*

A principal component analysis shows that 79% of the variance of the four parameters can be explained by two axes in a principal component analysis (PCA). The first axis explains 57%, the second axis 22%. The parameter sets can be clustered in two groups, significantly clustering on the scores for the first PCA axis. Fig. 6(e) shows the zones that were delineated with the parameter set approach. Here a gradient from north-west to south-east is observed, with an interference of both clusters in the sandy region.

3.5. *A priori clustering in three hydrological regions*

It is known that Flanders can be clustered in at least three hydrological regions. This clustering based on flow and catchment characteristics cannot be ignored while investigating the geographical spread of PDM parameter values. It was found (Voet, 2000) that the regression between catchment characteristics and flow regime within these regions was more significant compared with the overall regression. Recent research indicates that the main differences between regions can be explained by geological properties, combined with slope, soil and land use (Cabus et al., 2007). Other surface properties (area, river network, shape) fine-tune flow characteristics in the region.

When combining these hydrological clusters in Flanders with the zones depicted above, one observes the similarity. Several parameter clusters coincide with one or two hydrological cluster zones.

The variation in parameter optima within each of the three hydrological regions is expected to be small compared with the overall variation. Table 3 gives the average parameter values per hydrological region. An ANOVA shows that the differences between the three groups are significant for the

Table 3 – Averaged PDM parameter values for the three hydrological regions in Flanders (all catchments included)

	Hilly loam (HQHCV)	Dry loam (LQHCV)	Sand (LQLCV)
c_{max} (mm)	358	1563	917
c_{min} (mm)	28	122	45
b	0.56	0.32	0.54
k_1 (h)	13.9	12.1	19.4
K_2 (h)	3.9	3.6	5.5
k_b (h/mm^2)	5.5	666.6	12.2
k_g (h)	6080	16,679	9326
S_t (mm)	20	28	15
q_{const} (m^3/s)	−0.001	−0.4	−0.092

values of parameters c_{max} ($p < 0.001$ for null hypothesis of equality), c_{min} ($p < 0.001$), b ($p < 0.001$), k_1 ($p = 0.007$), k_b ($p = 0.007$), k_g ($p < 0.001$) and q_{const} ($p = 0.012$).

The clustering in three hydrological groups explains more variation of the first axis of the PCA ($\chi^2 = 53.232$, $p < 0.001$) than the parameter set approach ($\chi^2 = 13.767$, $p < 0.001$).

The different hydrological behaviour is clearly expressed in different PDM parameter values. This is illustrated by the mean distribution of the soil moisture reservoirs (Pareto distribution) in the three regions (Fig. 7).

The set for the sandy region (LQLCV) is characterized by relatively high-recharge rates k_g and deepest soil moisture reservoir depth c_{max}. The example of the Grote Nete in Hulshout can be considered as representative for this region. S_{max} (average soil moisture reservoir depth) is 600 mm, which is close to the average for Flanders (645 mm). The b-value is relatively high.

The parameter sets for the dry loamy region (LQHCV) are characterized by very high values for k_g and c_{max}. Here the average S_{max} is 1210 mm, among the highest values found in Flanders. The standard deviation on these values is high. This region is less uniform than the other two, which can be attributed mostly to a non-uniform geology (Cabus et al., 2007). The storage time constants for runoff are relatively small. The small runoff volume (maximum S_{max}) is drained off with high and narrow peaks (small routing time constants k_1 and k_2).

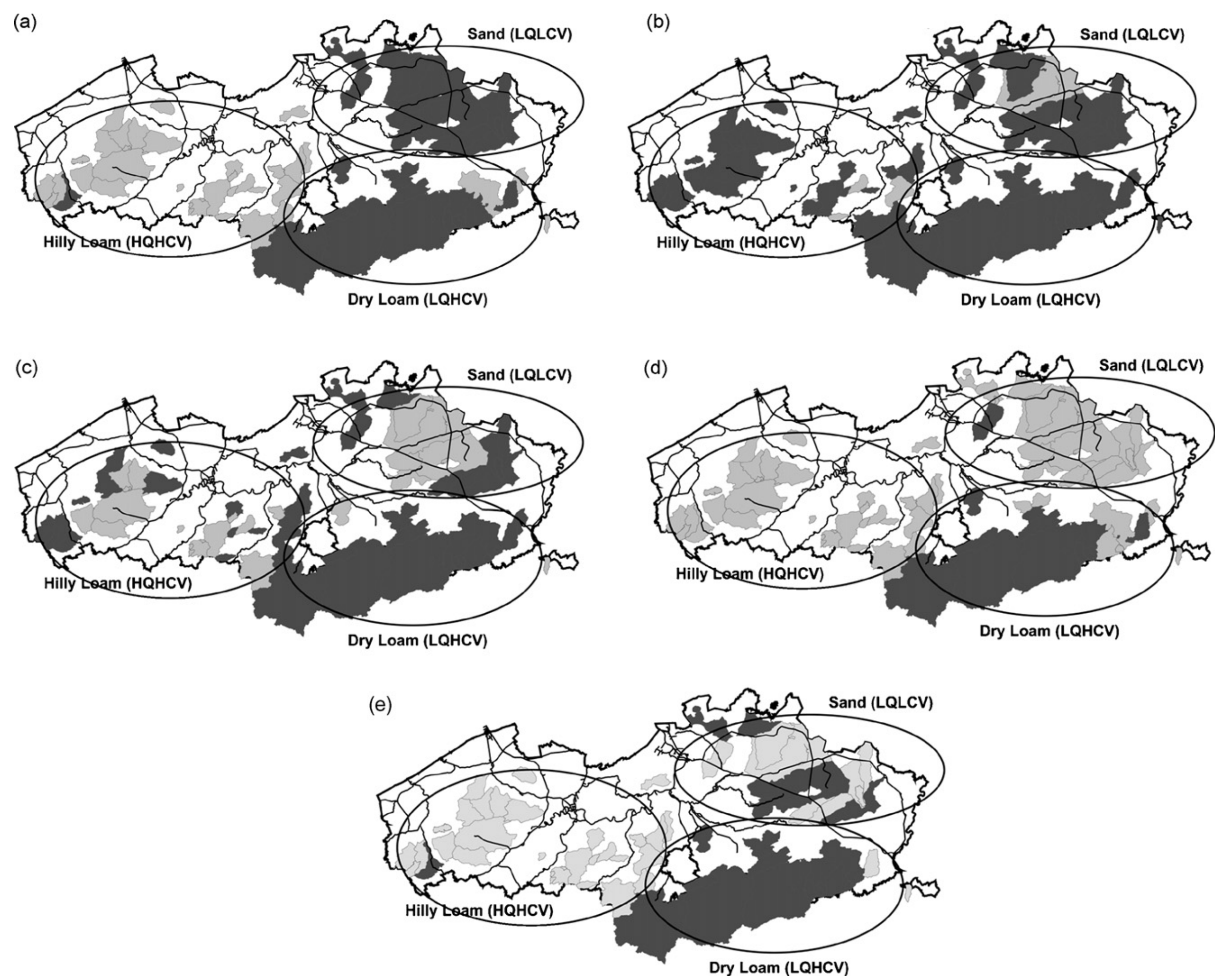

Fig. 6 – Zones with uniform parameter values within Flanders with the single-parameter approach (a: C_{max}; b: C_{min}; c: b; d: k_g) and the parameter set approach (e). The clusters are indicated by the colour of the catchments. The three hydrological zones are indicated by the ellipses.

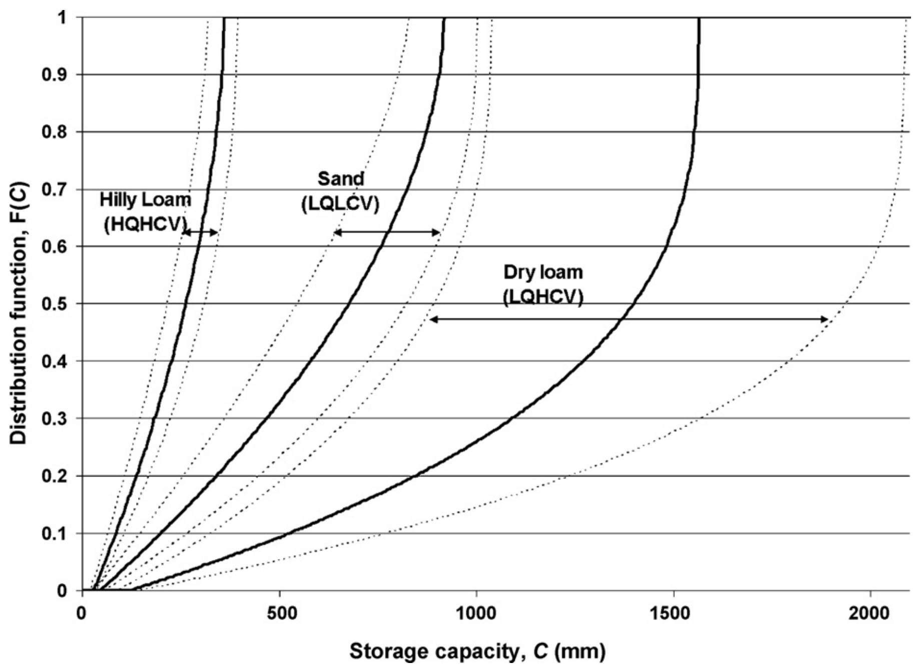

Fig. 7 – Pareto distribution function of storage capacity for the three hydrological regions (all catchments included). Mean distribution (solid line) and 95% confidence intervals (dashed line).

The set from the hilly area in the west of Flanders (HQHCV) is characterized by very small k_g and c_{max} values. Average S_{max} is 240 mm. The share of runoff in river flow is very large in these areas. The peaked flows are approximated with relatively small routing time constants.

One can conclude that the a priori clustering in known hydrological regions explains more than blind clustering, purely based on parameter values. It is clear that the PDM concept reflects the physical processes at the catchment scale. The values of the PDM parameters are largely influenced by the catchment characteristics, which is reflected in the geographical spread of parameters.

4. Conclusion

The PDM is applied in many countries (England, India, Thailand, ...). In Flanders (Belgium) too, it has been applied successfully on several occasions. Over the past years, a consistent and area-covering simulation has been carried out for all river-gauging stations on the non-navigable watercourses. A total of 98 PDMs have been configured. These models were assessed not only for the accurate simulation of a limited number of selected storms, but also for their statistical correspondence with high-water events, their total water volume and the total similarity over the complete year-to-year monitoring series. In all, 1456 years were modelled in this way, with an average NSE coefficient of 0.58. The PDM concept appears to be well suited to simulate the runoff in Flemish catchments. From the parameter values, it is also possible to identify a strong geographical component. This component can be identified in both a single-parameter approach and a parameter set approach. Both approaches clearly indicate the geographical influence on respectively single-parameter values and parameter combinations. Although a combination of both approaches clearly gives a better view of parameter behaviour, the a priori clustering in known hydrological clusters gives additional and more detailed information compared with both single parameter and parameter set approaches. The parameter set from the hydrological region will give more accurate results in an ungauged catchment when compared with a parameter set from either the single parameter or parameter set approaches. Detailed knowledge about the modelled catchments and their runoff behaviour is essential for an optimal interpretation and clustering of model parameters. The clustering in the three hydrological regions in Flanders is strongly reflected in the parameter values.

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